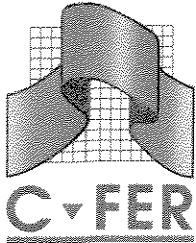


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Prioritization of Onshore Pipeline Systems for Integrity Maintenance

AN

**PIRAMID Technical
Reference Manual No. 4.1**

**Confidential to
C-FER's Pipeline Program
Participants**

**Prepared by
M. J. Stephens, M.Sc., P.Eng.**

Centre For Engineering Research Inc.

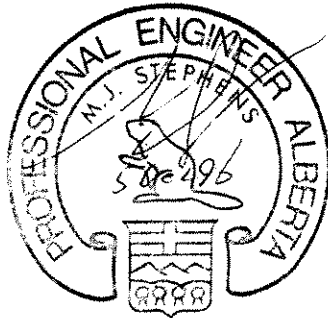
**November 1996
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<p>PERMIT TO PRACTICE CENTRE FOR ENGINEERING RESEARCH INC.</p> <p>Signature: <u>M. J. Stephens</u></p> <p>Date: <u>5/12/96</u></p> <p>PERMIT NUMBER: P4487 The Association of Professional Engineers, Geologists and Geophysicists of Alberta</p>

NOTICE

Restriction on Disclosure

This report describes the methodology and findings of a contract research project carried by the Centre For Engineering Research Inc. on behalf of the Pipeline Program Participants. All data, analyses and conclusions are proprietary to C-FER. This material contained in this report may not be disclosed or used in whole or in part except in accordance with the terms of the Joint Industry Project Agreement. The report contents may not be reproduced in whole or in part, or be transferred in any form, without also including a complete reference to the source document.

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EXECUTIVE SUMMARY

The Centre For Engineering Research Inc. (C-FER) is conducting a joint industry research program directed at the optimization of pipeline integrity maintenance activities using a risk-based approach. This document describes the system prioritization model that has been developed to estimate the level of operating risk associated with all segments within a pipeline system. This model forms the basis for one of the modules in the software suite *PIRAMID* (Pipeline Risk Analysis for Maintenance and Integrity Decisions).

The pipeline system prioritization approach involves the analysis of segment-specific pipeline attributes to produce firstly, an estimate of the probability of failure associated with individual segments as a function of failure cause, and secondly, an estimate of the potential consequences of segment failure in terms of three distinct consequence components (*i.e.*, life safety, environmental damage, and economic impact). The model then combines the cause-specific failure probability estimates with a global measure of the loss potential associated with the different consequence components into a single measure of operating risk for each pipeline segment. Segments are then ranked according to the estimated level of risk, the intention being to identify (or target) potentially high risk segments for subsequent detailed decision analysis at the maintenance optimization stage of the pipeline maintenance planning process.

Key steps in the pipeline system prioritization process are summarized as follows:

Probability Estimation

The annual probability of failure of each segment within the operating system is calculated for each significant failure cause from baseline historical failure rate estimates which are adjusted to reflect the impact of line-specific attribute sets. The specific failure causes addressed are: metal loss corrosion (external and internal); outside force (mechanical damage and ground movement); crack-like defects (stress corrosion cracking and seam weld fatigue cracks); and 'other'.

Baseline failure rates for a given pipeline type (*i.e.*, gas or liquid) are obtained from statistical analysis of historical pipeline incident data which yield estimates of the annual number of failure incidents per unit line length. The baseline failure rates are then converted to line-specific estimates using failure rate modification factors that depend on the attributes of the line segment in question. The failure rate modification factors are calculated from the values of selected segment attributes using algorithms developed from statistical analysis of pipeline incident data and/or analytical models supplemented where necessary by judgement. The resulting line-specific failure rates are then converted to failure probability estimates by multiplying each failure rate by the length of the corresponding line segment.

Executive Summary

Consequence Analysis

The consequences of failure associated with a given segment are estimated using analytical models. The approach assumes that the consequences of pipeline failure are fully represented by three parameters: the *total cost* as a measure of the economic loss, the *number of fatalities* as a measure of losses in life, and the *residual spill volume* (after initial clean-up) as a measure of the long term environmental impact. The consequence assessment approach involves: modelling the release of product from the pipeline; determination of the likely hazard types and their relative likelihood of occurrence; estimation of the hazard intensity at different locations; and calculation of the number of fatalities, the residual spill volume, and the total cost.

The three distinct consequence measures calculated using the models are combined into a single measure of the total loss potential associated with line failure by converting fatality estimates and residual spill volume estimates into equivalent costs. This conversion is carried out based on the so-called 'willingness to pay' concept which involves making an estimate of the amount of money that society would be willing to pay to avoid a particular adverse outcome.

Risk Estimation and Ranking

Multiplication of the segment-specific failure probability estimate for a given failure cause by the associated combined loss estimate (a financial cost estimate including the cost equivalent of human fatalities and residual spill volume) produces an estimate of operating risk defined as the expected annual loss associated with a given segment of pipeline for the failure cause in question. Summation of the risk estimates for all failure causes associated with a given segment gives an estimate of the total expected annual loss associated with segment operation. Dividing these segment risk estimates by the corresponding segment length yields normalized risk estimates that allow comparison of calculated risks between segments of different lengths. These cause-specific and combined-cause risk estimates form the basis for a quantitative ranking of all segments identified within a given pipeline system.

1.0 INTRODUCTION

1.1 Background

This document constitutes one of the deliverables associated C-FER's joint industry program on risk-based optimization of pipeline integrity maintenance activities. The goal of this program is to develop models and software tools that can assist pipeline operators in making optimal decisions regarding integrity maintenance activities for a given pipeline or pipeline segment. The software resulting from this joint industry program is called PIRAMID (Pipeline Risk Analysis for Maintenance and Inspection Decisions). This document is part of the technical reference manual for the program.

Implementation of a risk-based approach to maintenance planning, as envisioned in this program, requires quantitative estimates of both the probability of line failure and the adverse consequences associated with line failure should it occur. There is considerable uncertainty associated with the assessment of both the probability and consequences of line failure. To find the optimal set of integrity maintenance actions, in the presence of this uncertainty, a probabilistic optimization methodology based on the use of decision influence diagrams has been adopted. The basis for and development of this decision analysis approach is described in PIRAMID Technical Reference Manual No. 1.2 (Stephens *et al.* 1995). Application of the influence diagram based decision analysis approach to onshore pipeline systems is described in PIRAMID Technical Reference Manual No. 3.2 (Stephens *et al.* 1996).

Given the level of effort associated with the decision influence diagram approach to maintenance optimization, it is considered impractical and inefficient to carry out such a detailed analysis of candidate maintenance activities for all failure causes associated with each segment within a pipeline system. Alternatively, it is desirable to develop a pipeline system prioritization model that will estimate the level of operating risk associated with each segment within the system and to use this risk estimate as a basis for ranking segments. This segment ranking will serve to identify segments within the system with a potentially unacceptable level of operating risk with the intent that the high risk segments so identified can then be subjected to the more detailed analysis implicit in the decision influence diagram approach referred to above.

1.2 Objective and Scope

This document describes the system prioritization model that has been developed to estimate the level of operating risk associated with all segments within a pipeline system. The approach involves the analysis of segment-specific pipeline attributes to produce firstly, an estimate of the failure rate associated with individual segments as a function of failure cause, and secondly, an estimate of the potential consequences of segment failure in terms of three distinct consequence components (*i.e.*, life safety, environmental damage, and economic impact). The model will then

Introduction

combine the cause-specific failure rate estimates with a global measure of the loss potential associated with the different consequence components into a single measure of operating risk for each pipeline segment, and then rank each segment, by failure cause, according to the calculated level of risk. This model will therefore serve as a screening tool that will help pipeline operating companies identify potentially high risk segments for subsequent detailed analysis using the decision analysis tools that are currently being developed under this project.

The basic structure of the prioritization model described herein is based on the methodology developed in PIRAMID Technical Reference Manual No. 1.2 (Stephens *et al.* 1995). This document provides a detailed technical description of the prioritization approach and the underlying basis for the calculation of failure probabilities, individual and combined consequence components, and operating risk.

2.0 THE PRIORITIZATION METHOD

2.1 Overview

The framework for the pipeline integrity maintenance optimization as developed under this project is summarized in Figure 2.1. The first significant stage in the maintenance optimization process is to prioritize segments within a given pipeline system with respect to the need for integrity maintenance action. Specifically, the system prioritization stage is intended to rank segments based on the estimated level of operating risk associated with significant failure causes, where *risk* is defined as the product of the probability of line failure and a global measure of the adverse consequences of failure. To this end, pipeline characteristics (or attributes) must be evaluated to produce firstly, a line-specific estimate of the failure probability for each segment within the system as a function of failure cause (*e.g.*, metal loss corrosion, mechanical damage, ground movement, crack-like defects, *etc.*), and secondly, an estimate of the potential consequences of segment failure in terms of three distinct consequence components: life safety; environmental damage; and economic impact. Cause-specific failure probability estimates are then multiplied by a global measure of the loss potential associated with the different consequence components to produce a single measure of operating risk for all failure causes associated with each segment. Segments can then be ranked, by failure cause, according to the estimated level of risk. This cause specific segment ranking will serve to identify (or target) potentially high risk segments for subsequent detailed decision analysis at the maintenance optimization stage where the optimal strategy for managing the risk associated with a specific failure cause can be determined.

The steps associated with the prioritization process described above are summarized in the flowchart shown in Figure 2.2. The calculation process outlined in the flowchart can be divided into four distinct specification/calculation modules that perform the following functions:

- *System Definition.* defines the pipeline system to be analysed by specifying the segments to be considered and defining the attributes necessary to fully characterize each distinct section within each analysis segment.
- *Probability Estimation.* estimates the line-specific probability of failure, by failure cause, for each distinct section within each analysis segment.
- *Consequence Evaluation.* estimates the line-specific consequences of failure for each distinct section within each analysis segment.
- *Risk Estimation and Ranking.* calculates the operating risk associated with each segment within the system on a cause by cause basis and ranks the segments by the calculated level of operating risk on either a cause-by-cause or a combined cause basis.

An expanded description of each functional module is given in the following sections.

The Prioritization Method

2.2 Model Components

2.2.1 System Definition

The extent of the pipeline system to be evaluated must first be defined. To this end, the pipeline system is divided into appropriate segments that can be treated as individual units with respect to integrity maintenance. For each segment the attributes that effect the probability and consequences of line failure are specified. Each segment should be as uniform as possible with respect to the attributes that affect pipe integrity (*e.g.*, age, material properties, coating type and environmental conditions). Alternatively, the segments may correspond to portions of the line for which the integrity maintenance actions being considered can be implemented (*e.g.*, if pigging is considered then a segment must be piggable and have pig traps at both ends). The preferred approach is subdivision by attribute commonality because the segment risk ranking results will then apply equally to all points along each segment. Where subdivision according to criteria other than attribute commonality is adopted, the segment ranking results will reflect an averaging process that accounts for variations in failure rates and failure consequences along the length of segments.

A detailed discussion of the System Definition model information requirements is given in Section 3.0.

2.2.2 Probability Estimation

The annual probability of failure of each segment within the operating system is calculated for each significant failure cause from baseline historical failure rate estimates which are adjusted to reflect the impact of line-specific attribute sets. The specific failure causes addressed are: metal loss corrosion (external and internal); outside force (mechanical damage and ground movement); crack-like defects (stress corrosion cracking and seam weld fatigue cracks); and 'other'.

Baseline failure rates for a given pipeline type (*i.e.*, gas or liquid) are obtained from statistical analysis of historical pipeline incident data which yield estimates of the annual number of failure incidents per unit line length. The baseline failure rates are then converted to line-specific estimates using failure rate modification factors that depend on the attributes of the line segment in question. The failure rate modification factors are calculated from the values of selected segment attributes using algorithms developed from statistical analysis of pipeline incident data and/or analytical models supplemented where necessary by judgement. The resulting line-specific failure rates are then converted to failure probability estimates by multiplying each failure rate by the length of the corresponding line segment.

A detailed discussion of the calculation process associated with the Probability Estimation model is given in Section 4.0.

The Prioritization Method

2.2.3 Consequence Evaluation

The consequences of failure associated with a given segment are estimated using analytical models. The approach assumes that the consequences of pipeline failure are fully represented by three parameters: the *total cost* as a measure of the economic loss, the *number of fatalities* as a measure of losses in life, and the *residual spill volume* (after initial clean-up) as a measure of the long term environmental impact. The consequence assessment approach involves: modelling the release of product from the pipeline; determination of the likely hazard types and their relative likelihood of occurrence; estimation of the hazard intensity at different locations; and calculation of the number of fatalities, the residual spill volume, and the total cost. The consequence models employed in the prioritization process have been adapted from the models previously developed for use in the decision analysis model based on influence diagrams (see PIRAMID Technical Reference Manual No. 3.2, Stephens *et al.* 1996).

The hazard types considered in the modelling process include both the immediate hazards associated with line failure (*e.g.*, jet/pool fires, vapour cloud fires or explosions, and toxic or asphyxiating clouds) as well as the long term environmental hazards associated with persistent liquid spills. Fatality estimation, based on the hazard characterization models, reflects the population density associated with a given land use and takes into account the effect of shelter and/or escape on survivability. Estimation of residual spill volume takes into account the product clean-up potential associated with the spill site and incorporates a factor that adjusts the volume measure to reflect both the environmental damage potential of the spilled product as well as the damage sensitivity of the environment in the vicinity of the spill site. The total cost estimate includes: the direct costs associated with line failure including the cost of lost product, line repair, and service interruption; and the costs that are dependent on the type of release hazard including the cost of property damage, spill clean-up, and fatality compensation.

The three distinct consequence measures calculated using the models are combined into a single measure of the total loss potential associated with line failure by converting fatality estimates and residual spill volume estimates into equivalent costs. This conversion is carried out based on the so-called 'willingness to pay' concept which involves making an estimate of the amount of money that society would be willing to pay to avoid a particular adverse outcome.

A detailed discussion of the calculation process associated with the Consequence Evaluation model is given in Section 5.0.

2.2.4 Risk Estimation and Ranking

Multiplication of the segment-specific failure probability estimate for a given failure cause by the associated combined loss estimate (a financial cost estimate including the cost equivalent of human fatalities and residual spill volume) produces an estimate of operating risk defined as the expected annual loss associated with a given segment of pipeline for the failure cause in question. Summation of the risk estimates for all failure causes associated with a given segment gives an

The Prioritization Method

estimate of the total expected annual loss associated with segment operation. Dividing these segment risk estimates by the corresponding segment length yields normalized risk estimates that allow comparison of calculated risks between segments of different lengths. These cause-specific and combined-cause risk estimates form the basis for a quantitative ranking of all segments identified within a given pipeline system.

A detailed discussion of the calculation process associated with the Risk Estimation and Segment Ranking model is given in Section 6.0.

Figures

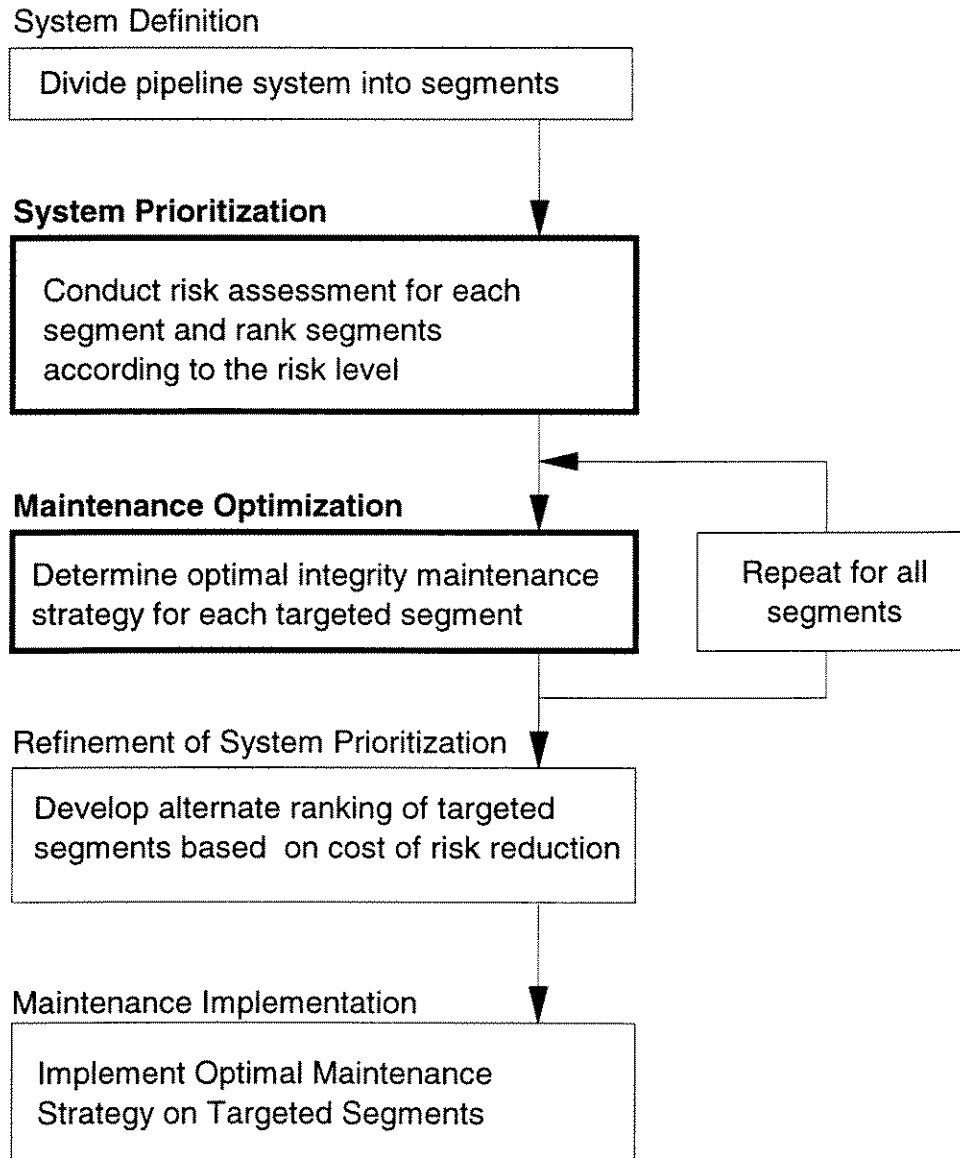


Figure 2.1 Framework for risk-based optimization of pipeline integrity maintenance activities

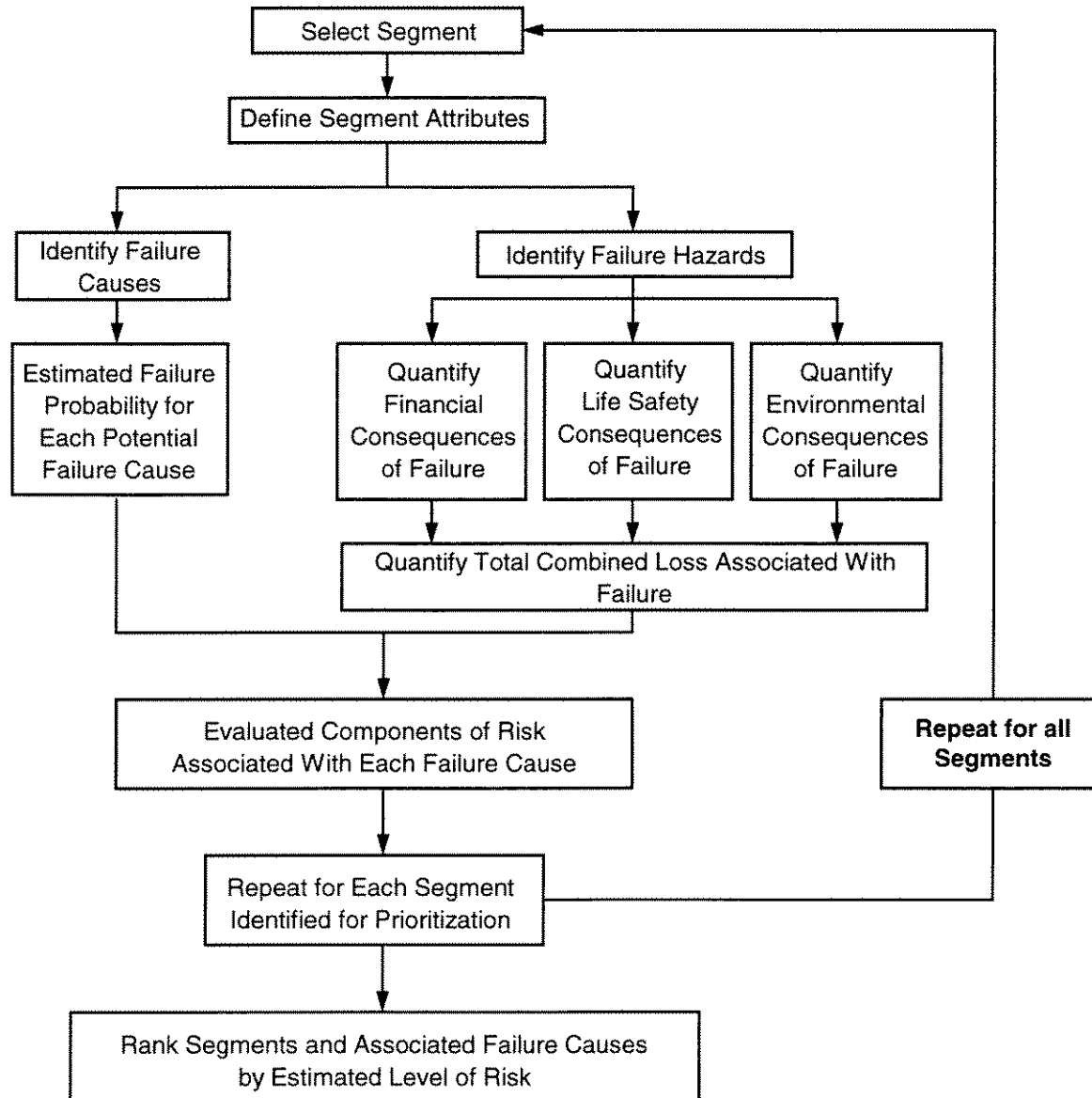


Figure 2.2 Flow chart for pipeline system prioritization

3.0 SYSTEM DEFINITION

3.1 Introduction

The pipeline system is defined by specifying the pipeline segments that are to be analysed and the required line attributes along the length of each analysis segment. This information will be processed to produce a description of each analysis segment that identifies consecutive sections within each segment (where a *section* is defined as a length of pipeline over which the attribute values do not vary) and defines the attribute set associated with each section.

3.2 Pipeline Attributes

The specific pipeline attributes that have been chosen as a basis for segment prioritization are summarized in Table 3.1. The chosen attributes involve two overlapping sub-sets, one associated with parameters that have been shown to have an impact on the rate, and hence the probability, of line failure, and the other with parameters that are known to significantly influence the consequences of line failure should it occur. Table 3.1 identifies the specific attributes associated with each sub-set. Note that the total number of attributes that must be defined for each segment in a given system depends on the type of product (*i.e.*, natural gas, HVP liquid, or LVP liquid) being transported in the line and whether or not the environmental impact of persistent liquid product spills is to be considered in the consequence evaluation.

Note also that the attribute set employed for probability estimation and consequence evaluation at the prioritization stage is not intended to be comprehensive (*e.g.*, the pipeline literature suggests that line-specific failure rates are influenced by attributes not considered in the prioritization model). A restricted attribute set has purposely been employed at the system prioritization stage to limit the information requirements associated with the system prioritization activity. In addition, it is noted that the impact of additional factors on the probability and consequences of failure are addressed at the subsequent maintenance optimization stage where a more detailed estimate of operating risk is calculated as part of the formal decision analysis process conducted for the segments targeted by the initial risk ranking at the prioritization stage.

Tables

No.	Attribute Description	Attribute Name	Units ext (int)	Input Type	Required for Probability Estimation	Required for Consequence Estimation	Analysis Preferences		
							Natural Gas only	HVP liquids only	LVP liquids included consider env. suppress env.
1	Pipe Diameter	PipeDia	mm (m)	S1	X	X	X	X	X
2	Pipe Wall Thickness	PipeWall	mm (m)	S1	X	X	X	X	X
3	Pipe Body Yield Strength	PipeYield	MPa (Pa)	S1	X	X	X	X	X
4	Pipe Body Seam Weld Type	SeamType		S2	X	X	X	X	X
5	Pipe Joint Type	JointType		S2	X	X	X	X	X
6	Line Age	LineAge	years	S1	X	X	X	X	X
7	Line Elevation Profile	ElevProfile	m	C1		X	X	X	X
8	Operating Pressure Profile	PressProfile	kPa (Pa)	C1	X	X	X	X	X
9	Operating Pressure Range	PressRange	kPa (Pa)	S1	X	X	X	X	X
10	Cumulative Number of Pressure Cycles	PressCycle		S1	X	X	X	X	X
11	Operating Temperature	LineTemp	°C (K)	S1	X	X	X	X	X
12	Product Flow Rate (sign denotes flow direction)	FlowRate	kg/s	S1		X	X	X	X
13	Line Volume (percentage of line capacity)	CapFracton	% (fraction)	S1		X	X	X	X
14	Billing Abatement Threshold (percentage of nominated volume)	BAT	% (fraction)	S1		X	X	X	X
15	Product Transportation Distance	TransDist	km (m)	S1		X	X	X	X
16	Block Valve Spacing	ValveSpace	km (m)	S1		X	X	X	X
17	Time to Block Valve Closure	TimeClose	min (sec)	S1		X	X	X	X
18	Detectable Release Volume	VolDetect	cu. m.	S1		X	X	X	X
19	Time to Leak Detection	TimeDetect	hrs (sec)	S1		X	X	X	X
20	Time to Leak Stoppage (from time of detection)	TimeStop	hrs (sec)	S1		X	X	X	X
21	Depth of cover	Cover	m	S1	X	X	X	X	X
22	Adjacent Land Use	AdjLand		S2	X	X	X	X	X
23	ROW Accessibility	ROWAccess		S2	X	X	X	X	X
24	ROW Condition	ROWCond		S2	X	X	X	X	X
25	ROW Patrol Frequency	ROWPatrol		S2	X	X	X	X	X
26	Notification & Response System	Notify		S2	X	X	X	X	X
27	Crossing Type / Special Terrain Features	Crossing		S2	X	X	X	X	X
28	Near Field Terrain Characteristics	NFTerrain		S2		X	X	X	X
29	General Soil Corrosivity	SoilCorrode		S2	X	X	X	X	X
30	SCC Potential of Soil Environment	SCCPotential		S2	X	X	X	X	X
31	External Pipe Coating Type	ExtCoating		S2	X	X	X	X	X
32	External Pipe Coating Condition	CoatCond		S2	X	X	X	X	X
33	Cathodic Protection Level	CPLLevel		S2	X	X	X	X	X
34	Presence of Coating Shielding	CoatShield		S2	X	X	X	X	X
35	Presence of Electrical Interference or Casing Short	Interference		S2	X	X	X	X	X
36	Product Corrosivity	ProdCorrode		S2	X	X	X	X	X
37	Ground Movement Potential	GndMovPot		S2	X	X	X	X	X
38	Pipe Fail Potential given Ground Movement	GndFailPot		S2	X	X	X	X	X
39	Surface water within 300m	SurfWater		S2		X	X	X	X
40	Drinking Water within 5 km	DrkWater		S2		X	X	X	X
41	Other Water within 5 km	OthWater		S2		X	X	X	X
42	Land Use within 5 km	DirExposure		S2		X	X	X	X
43	Sensitive Environment within 10 km	SensEnviro		S2		X	X	X	X
44	Sensitive Groundwater within 10 km	SensGndWtr		S2		X	X	X	X

Attribute Data Input Type
S1 all consecutive sections delineated by KP start & KP end, defined by numeric value
S2 all consecutive sections delineated by KP start & KP end, defined by text string from predefined choice list
C1 continuously varying quantity defined by numeric values at KP reference locations

Table 3.1 Pipeline segment attributes for prioritization

4.0 PROBABILITY ESTIMATION

4.1 Introduction

An estimate is required of the annual probability of failure for each section within each analysis segment as a function of failure cause. In addition, since the consequences of line failure will depend on the mode of failure (*i.e.*, leak or rupture), because the failure mode will affect product release and hazard characteristics (see Section 5.0), it is also necessary to estimate failure probability as a function of failure mode. The required mode- and cause-specific failure probabilities can be calculated from baseline failure rate estimates adjusted to reflect the impact of line specific attribute sets.

Baseline failure rate estimates for a given pipeline product (*i.e.*, gas or liquid) can be estimated from historical pipeline incident data. These baseline failure rates can be converted to section-specific estimates using failure rate modification factors that are defined by failure mode and failure cause as a function of selected pipeline section attributes. The failure rate modification factors are calculated from the section attributes using algorithms developed from the analysis of historical pipeline incident data and expert judgement. The resulting section-specific failure rates can subsequently be converted into failure probability estimates by multiplying each failure rate by the length of the corresponding section.

4.2 Probability Estimation Model

4.2.1 General

The annual probability of failure Pf for each section j within each analysis segment i , as a function of failure mode k and failure cause l , can be calculated from the following:

$$Pf_{ijkl} = Rf_{ijkl} Lsec_{ij} \quad (\text{per year}) \quad [4.1]$$

where: Rf_{ijkl} = the failure rate associated with section j of segment i for failure mode k and failure cause l ;

$Lsec_{ij}$ = the length of section j within segment i (km);

and

$$Rf_{ijkl} = Rfb_l MF_{kl} AF_{ijl} \quad (\text{per km}\cdot\text{year}) \quad [4.2]$$

where: Rfb_l = the baseline failure rate for failure cause l (per km \cdot year);

Probability Estimation

MF_{kl} = the relative probability or mode factor for failure mode k associated with cause l ; and

AF_{ijl} = the failure rate modification factor for section j of segment i associated with failure cause l .

The specific failure modes (index k) considered by the probability estimation model are:

- small leaks ($k = 1$);
- large leaks ($k = 2$); and
- ruptures ($k = 3$).

The significant failure causes (index l) addressed by the probability estimation model are:

- external metal loss corrosion ($l = 1$);
- internal metal loss corrosion ($l = 2$);
- mechanical damage ($l = 3$);
- ground movement ($l = 4$);
- environmentally induced crack-like defects, specifically stress corrosion cracking ($l = 5$);
- mechanically induced crack-like defects, specifically seam weld fatigue ($l = 6$); and
- other ($l = 7$).

4.2.2 Baseline Failure Rates

The failure rate is defined as the annual number of incidents involving loss of containment divided by the length of pipeline in operation for the year in which incidents are reported. The baseline failure rate, Rfb , is defined herein as the average failure rate for a reference line segment associated with a particular pipeline system, operating company or industry sector (*i.e.*, gas or liquid). It is intended to reflect average conditions relating to construction, operation and maintenance practices. For a given pipeline system these baseline failure rate estimates are best obtained from operating company data if the system exposure (*i.e.*, the total length and age of the system) is sufficient to yield a statistically significant number of failure incidents. In the absence of appropriate company or system specific data, an estimate of the baseline failure rate can be obtained from historical pipeline incident and exposure data gathered and published by government regulatory agencies, industry associations, and consultants.

In a previous related project (see Appendix B, Stephens *et al.* 1996) a review of onshore pipeline incident data and statistical summary reports was carried out to facilitate the development of a set of reference failure rates that could be taken to be representative of natural gas, crude oil and petroleum product pipelines as a whole. Allowing for differences in the incident reporting requirements associated with the different reporting agencies, and recognizing that in the context of the risk estimation approach adopted herein, we are interested in rate estimates that include

Probability Estimation

'small leaks' which are often not reported, the review supports a reference failure rate of approximately 1×10^{-3} per km•yr for both gas and liquid product pipelines.

The reference failure rate cited above is a combined failure cause estimate. As part of another related project (Stephens *et al.* 1995) estimates of the relative probabilities of failure for each significant failure cause were obtained for natural gas and liquid product pipelines based on data compiled by Canadian and American regulatory agencies. The data supports the following relative probability estimates for both gas and liquid lines:

<u>Failure Cause</u>	<u>Relative Probability</u>
External Metal Loss Corrosion	30%
Internal Metal Loss Corrosion	5%
Mechanical Damage	30%
Ground Movement	(see note)
Environmentally Induced Cracks (stress corrosion cracking)	(see note)
Mechanically Induced Cracks (metal fatigue)	(see note)
Other (excluding mechanical components)	20%

Note: values either not available for cause as defined, or too low to be significant in a general context.

Multiplying the reference failure rates by the relative failure probability estimates tabulated above leads to the cause-specific baseline failure rate summarized in Table 4.1. Note that baseline values are not tabulated for causes involving ground movement and crack-like defects. This reflects the assumption that these failure causes are highly location or line specific (as opposed to being a common problem for all pipelines) and the associated failure rates are therefore not adequately characterized using the adjusted baseline failure rate approach described above. Instead, an approach to probability estimation that keys on the specific attributes of the line in question will be employed for these failure causes. The specific approach adopted for each of the three excepted failure causes will be described in the sections of the report that develop their respective attribute factor algorithms.

4.2.3 Failure Mode Factor

The relative probability of failure by small leak, large leak, or rupture will depend on the failure mechanism being considered. For example, metal loss corrosion failures are predominantly small leaks (*i.e.*, pin holes) whereas mechanical damage failures resulting from excavation equipment typically involve a greater percentage of large leaks and ruptures.

Probability Estimation

In the context of this project, the distinction between the three failure modes is tied to the hole size, or more explicitly, the equivalent circular hole diameter. Pipeline failure rate summaries that report failure mode data by equivalent hole size (*e.g.*, Fearnough 1985, and EGIG 1993) typically define the transition from small leak to large leak by an equivalent hole diameter of 20 mm, and the transition between large leak and rupture by an equivalent diameter ranging from 80 mm (Fearnough 1985) to the line diameter (EGIG 1993). Based on this approach to failure mode distinction, the above references suggest relative failure mode probabilities for gas transmission pipelines in the following ranges:

<u>Failure Cause</u>	<u>Small Leak</u>	<u>Large Leak</u>	<u>Rupture</u>
Corrosion	85 to 95 %	5 to 10 %	0 to 5 %
External Interference	20 to 25 %	50 to 55 %	20 to 30 %
Ground Movement	10 to 20 %	35 to 45 %	35 to 45 %
Construction Defects / Material Failure	55 to 70 %	25 to 35 %	5 to 10 %
Other / Unknown	70 to 90 %	5 to 15 %	5 to 15 %

In the absence of similar failure mode data for liquid product lines it is suggested that the above range estimates be assumed to apply to both gas and liquid product lines. Reference failure mode probability estimates based on this assumption are summarized in Table 4.1.

4.2.4 Failure Rate Modification Factors

The algorithms required to define the failure rate modification factor AF_{ij} for each significant failure cause l , for a given section j of segment i , are developed in the following sections.

4.2.4.1 External Metal Loss Corrosion

Pipeline failure associated with external metal loss corrosion is typically the result of a loss of coating protection at locations where the surrounding soil environment supports a corrosion reaction. The factors that affect the susceptibility of a line to external corrosion include: the type and condition of the coating system; the level of cathodic protection; and the corrosivity of the surrounding soil medium. Also, the corrosivity of the environment and the general condition of the coating system are significantly affected by the operating temperature of the pipeline because high temperatures promote coating decay and accelerate chemical reactions. Because external corrosion is a time dependent mechanism, the extent of corrosion damage and its propensity to cause line failure will be significantly influenced by the duration of exposure (*i.e.*, the line age) and the thickness of the pipe wall that must be penetrated by the growing corrosion feature.

Probability Estimation

The failure rate modification factor developed to reflect the impact of these factors on the baseline external metal loss failure rate is

$$AF = K_{EC} \left[\frac{A}{t} (T + 17.8)^{2.28} \right] F_{SC} F_{CP} F_{CT} F_{CC} \quad [4.3]$$

where: K_{EC} = model scaling factor;
 A = line pipe age;
 t = line pipe wall thickness;
 T = line operating temperature;
 F_{SC} = soil corrosivity factor;
 F_{CP} = cathodic Protection factor;
 F_{CT} = coating type factor; and
 F_{CC} = coating condition factor.

The core relationship involving line age A wall thickness t and operating temperature T (line attributes: **LineAge**, **PipeWall**, and **LineTemp** in Table 3.1) was developed from a multiple linear regression analysis of failure rate data on hydrocarbon liquid pipelines operating in California published by the California State Fire Marshall (CSFM 1993). It should be noted that the actual relationship derived from the California pipeline incident data involved line diameter rather than wall thickness. The diameter term was translated into a wall thickness term (which, in the context of corrosion failure, is considered to be the more relevant parameter) by assuming that wall thickness is directly proportional to line diameter.

The soil corrosivity factor F_{SC} (line attribute **SoilCorrode** in Table 3.1) is an index that scales the rate modification factor over a range that reflects the impact of variations in soil corrosivity on the corrosion failure rate. The index multiplier associated with each value of the soil corrosivity attribute is given by the following:

F_{SC}	<u>Soil Corrosivity</u>	<u>Resistivity (ohm•cm)</u>	<u>Soil Drainage - Texture</u>
0.33	low	> 10,000	excessively drained - coarse texture
0.67	below average	5000 - 10,000	well drained - moderately coarse texture, or poorly drained - coarse texture
1.0	average	2000 - 5000	well drained - moderately fine texture, or poorly drained - moderately coarse texture, or very poorly drained with high steady water table
2.3	above average	1000 - 2000	well drained - fine texture, or poorly drained - moderately fine texture, or very poorly drained with fluctuating water table
3.3	high	< 1000	poorly drained - fine texture, or mucks, peats with fluctuating water table

Probability Estimation

The order of magnitude range was established based on the results of corrosion metal loss tests conducted on steel pipe samples buried in soils of various resistivities as reported by Crews (1976). The corrosivity categories and corresponding resistivity ranges (together with descriptions of characteristic soil conditions) were adapted from those developed by Miller *et al.* (1981) as a basis for ranking the underground corrosion potential based on soil surveys.

The cathodic protection factor F_{CP} (line attribute **CPlevel** in Table 3.1) is an index that scales the rate modification factor over a range that reflects the impact of varying degrees of cathodic protection system effectiveness on corrosion failure rate. The index multiplier associated with each value of the cathodic protection level attribute is given by the following:

F_{CP}	<u>Cathodic Protection Level</u>	<u>Characterization</u>
0.5	above average	adequate voltage, uniform level
1.0	average	adequate average voltage, some variability
3.0	below average	inadequate voltage and/or high variability
5.0	no cathodic protection	_____

The order of magnitude range was established primarily based on the failure rate data reported by the CSFM (1993) which indicates a failure rate approximately five times higher for unprotected pipe. The 0.5 and 3.0 factors were introduced based on judgement to reflect the fact that the five fold reduction in failure rate is an average value which therefore applies to pipelines having average cathodic protection levels and that some allowance should be made for above and below average conditions.

Note that the impact of two additional line attributes, the presence of coating shielding (attribute **CoatShield** in Table 3.1), and electrical interference (attribute **Interference** in Table 3.1), are tied to the cathodic protection factor. The assumption implicit in the model developed herein is that if either shielding or interference exists, then the cathodic protection factor will be set equal to the 'no protection' state (F_{CP} index = 5.0) to reflect the adverse effect of these characteristics on the overall effectiveness of the cathodic protection system.

The coating type factor F_{CT} (line attribute **ExtCoat** in Table 3.1) is an index that scales the rate modification factor to reflect the impact of different coating types on corrosion failure rate. The index multiplier associated with each coating type is given by the following:

F_{CT}	<u>Coating Type</u>
0.5	polyethylene / epoxy
1.0	coal tar
2.0	Asphalt

Probability Estimation

4.0	tape coat
8.0	none (bare pipe)

The reference coating types and the index multipliers were adapted from a study by Keifner *et al.* (1990) wherein index factors are cited based on the 'perceived track record' of generic coating types.

The coating condition factor F_{cc} (line attribute **CoatCond** in Table 3.1) is an index that scales the rate modification factor to reflect the impact of the condition of the external coating on corrosion failure rate. The index multiplier associated with each condition state is given by the following:

F_{cc}	<u>Coating Condition</u>
0.5	above average
1.0	average
2.0	below average

The coating condition states and associated indices were selected so that when taken together with the coating type factor described above, the product of the two coating factor indices will yield a set of multipliers that are similar to those proposed by Keifner *et al.* (1990) for the different coating types identified.

The model scale factor K_{ec} serves to adjust the failure rate modification factor to a value of unity for the *external corrosion reference segment* defined as the line segment associated with the reference value of all line attributes that influence the external metal loss failure rate estimate. The intention is that the baseline failure rate for external corrosion should apply directly to the reference segment (hence the need for a corresponding attribute modification factor of 1). The expression for K_{ec} is obtained by first rearranging Equation 4.3 and setting $AF = 1.0$ to give

$$K_{EC} = \frac{1}{\left[\frac{A}{t} (T + 17.8)^{2.28} \right] F_{SC} F_{CP} F_{CT} F_{CC}} \quad [4.4]$$

The value of external corrosion model scale factor is calculated using Equation [4.4] by substituting the values of all parameters that are associated with the reference segment. The reference segment parameter values should be developed in conjunction with the baseline failure rate estimate (see Section 4.2.2) on a pipeline system, operating company or industry basis, depending on the intended application of the model.

Probability Estimation

Based on a review of incident data summaries in the public domain the following reference values are suggested as default values for the external corrosion reference segment:

- line age, **LineAge** = 38 years;
- wall thickness, **PipeWall** = 5.82 mm;
- operating temperature, **LineTemp** = 36.6° C;
- soil corrosivity, **SoilCorrode** = Average ($F_{sc} = 1.0$);
- cathodic protection, **CPIlevel** = Average ($F_{cp} = 1.0$);
- coating type, **ExtCoating** = Coal Tar ($F_{ct} = 1.0$); and
- coating condition, **CoatCond** = Average ($F_{cc} = 1.0$).

The corresponding model scale factor is $K_{ec} = 1.69 \times 10^{-5}$.

4.2.4.2 Internal Metal Loss Corrosion

Pipeline failure associated with internal metal loss corrosion is primarily influenced by the corrosivity of the transported product. Like external corrosion, internal corrosion is a time dependent mechanism, the extent of corrosion damage and its propensity to cause line failure will therefore be significantly influenced by the duration of exposure (*i.e.*, the line age) and the thickness of the pipe wall that must be penetrated by the growing corrosion feature.

The failure rate modification factor developed to reflect the impact of these factors on the baseline internal metal loss failure rate is

$$AF = K_{IC} \left(\frac{A}{t} \right) F_{PC} \quad [4.5]$$

where: K_{IC} = model scaling factor;
 A = line pipe age;
 t = line pipe wall thickness; and
 F_{PC} = product corrosivity factor.

The core relationship involving line age A (line attribute **LineAge** in Table 3.1) and wall thickness t (line attribute **PipeWall** in Table 3.1) was inferred from the model developed for external corrosion which suggests that the failure rate is directly proportional to line age and inversely proportional to wall thickness. The line operating temperature term was dropped because the effect of temperature on the failure rate is covered under the broadly defined measure of product corrosivity.

The product corrosivity factor F_{PC} (line attribute **ProdCorrode** in Table 3.1) is an index that scales the rate modification factor over a range that reflects the impact of variations in product

Probability Estimation

corrosivity on corrosion failure rate. The index multiplier associated with each value of the product corrosivity attribute is given by the following:

F_{PC}	Product Corrosivity	Growth Rate (mm/yr)
0.04	negligible	< 0.02
0.2	low	0.02 to 0.1
1.0	moderate	0.1 to 0.5
5.0	high	0.5 to 2.5
25.0	extreme	> 2.5

The index range was established based on the simple assumption that if the corrosion growth rate is essentially constant, and failure rate has been shown to be inversely proportional to wall thickness, then it follows that the failure rate will be directly proportional to pit depth growth rate. The index multipliers are therefore directly proportional to the assumed growth rates for each product category. The corrosion growth rate ranges associated with each product category are consistent with values that are generally accepted in the process piping industry.

The model scale factor K_{IC} serves to adjust the failure rate modification factor to a value of unity for the *internal corrosion reference segment* defined as the line segment associated with the reference value of all line attributes that influence the external metal loss failure rate estimate. The intention is that the baseline failure rate for internal corrosion should apply directly to the reference segment (hence the need for a corresponding attribute modification factor of 1). The expression for K_{IC} is obtained by first rearranging Equation [4.5] and setting $AF = 1.0$ to give

$$K_{IC} = \frac{1}{\left(\frac{A}{t}\right) F_{PC}} \quad [4.6]$$

The value of internal corrosion model scale factor is calculated using Equation [4.6] by substituting the values of all parameters that are associated with the reference segment. The reference segment parameter values should be developed in conjunction with the baseline failure rate estimate (see Section 4.2.2) on a pipeline system, operating company or industry basis, depending on the intended application of the model.

Based on a review of incident data summaries in the public domain the following reference values are suggested as default values for the internal corrosion reference segment:

- line age, **LineAge** = 38 years;
- wall thickness, **PipeWall** = 5.82 mm; and
- product corrosivity, **ProdCorrode** = Moderate ($F_{PC} = 1.0$).

Probability Estimation

The corresponding model scale factor is $K_{IC} = 1.53 \times 10^{-4}$.

4.2.4.3 Mechanical Damage

4.2.4.3.1 Overview

Mechanical damage incidents are typically caused by construction or excavation equipment working in the area of the pipeline. The potential for line failure due to damage inflicted by this type of equipment depends on both the likelihood of mechanical interference and the subsequent likelihood of pipe failure given interference. The factors that affect the susceptibility of a line to mechanical interference include: 1) the level of construction/excavation activity on or near the right-of-way, which is influenced by the type of land use adjacent to the right-of-way and the presence of line crossings; and 2) the degree to which line burial depth, right-of-way condition and signage, first call systems, and line patrols reduce the potential for impact given activity. The potential for line failure given interference will depend on the type of equipment involved in the incident (*i.e.*, the level of force applied and configuration of the indenter) and the resistance of the pipe to a puncture type failure which is largely dependent on the thickness of the pipe wall and the strength of the line pipe material.

The failure rate modification factor developed to reflect the influence of these factors on the baseline mechanical damage failure rate is

$$AF = K_{MD} P_{HIT} P_{FIH} \quad [4.7]$$

where P_{HIT} is the relative probability of mechanical interference, P_{FIH} is the probability of line failure given interference, and K_{MD} is the model scaling factor.

4.2.4.3.2 Probability of Interference

The relationship developed to estimate the relative probability of mechanical interference (*i.e.*, the probability relative to the industry wide historical average value) is given by

$$P_{HIT} = [R_{ACT} P_{DPT} \{P_{MRK} P_{CALL} + P_{ACC} - (P_{MRK} P_{CALL} P_{ACC})\} \{P_{INT} + P_{DET} - (P_{INT} P_{DET})\}] \quad [4.8]$$

where:

- R_{ACT} = relative probability of construction activity;
- P_{DPT} = probability of inadequate cover depth;
- P_{MRK} = probability of inadequate line marking;
- P_{CALL} = probability of inadequate dig notification and response system;
- P_{ACC} = probability of accidental impact with marked and/or located line;
- P_{INT} = probability that patrol fails to detect activity (patrol interval too long); and
- P_{DET} = probability that patrol fails to detect activity (patrol personnel miss indication).

Probability Estimation

The basic relationships that describe the relative probability of mechanical interference as given by Equation [4.8] were obtained using the *fault tree analysis* method. A fault tree is a deductive model that can be constructed to identify the logical combinations of *basic events* leading to the main accidental event or *top event* being analysed, in this case, the occurrence of mechanical interference. It can be used to estimate the probability of the top event (mechanical interference) from the probabilities of the basic events (see for example McCormick 1981). The probability estimation approach adopted herein assumes that all basic events defined in the model are independent of one another.

The specific fault tree that was developed to model mechanical interference is shown in Figure 3.1. The first level of branching in the tree indicates that a hit occurs if: 1) there is excavation activity at the pipeline location; 2) the contractor fails to avoid the pipeline; and 3) the operating company's right-of-way patrols fail to detect the activity and prevent the damage. These events must all be true for the hit to occur and therefore they are connected with a so-called AND gate (*i.e.*, events must co-exist and probabilities are therefore multiplicative). Gate 2 states that excavation to pipeline location occurs if there is construction activity along the pipeline AND the excavation depth is deeper than the pipeline burial depth. Gate 3 indicates that the contractor will fail to avoid the pipeline if he is unaware of its presence or if he is aware of the pipeline but either ignores the warnings or simply hits the line by accident (these events need not all be true for the contractor to fail to avoid the pipeline, hence the use of a so-called OR gate which implies that the probabilities are additive). It is assumed that signage and a one-call systems are both used as warning mechanisms. Therefore, Gate 5 states that both of these warning methods must be inadequate for the contractor to be unaware of the presence of the pipeline. Finally, gate 4 indicates that the right-of-way patrols will fail to detect the activity if the interval between patrols is sufficiently long for the activity to start and the damage to occur between two patrols, OR if the patrol personnel fail to detect the activity.

The probabilities associated with representative states of all basic events required to specify the fault tree shown in Figure 3.1 are defined as follows.

The basic event associated with construction activity is defined by an annual probability of construction activity per unit length of pipeline relative to the activity level for a typical pipeline (*i.e.*, a relative rate estimate). This relative rate of construction activity, R_{ACT} is given by

$$R_{ACT} = 1.0F_{LU}F_{XING} \quad [4.9]$$

The land use factor F_{LU} (line attribute **AdjLand** in Table 3.1) is an index that scales R_{ACT} to reflect the influence of different land use types on construction activity level. The land use types and index multiplier associated with each type are given by the following:

Probability Estimation

E_{LU}	<u>Adjacent Land Use Type</u>
2.0	Commercial / Industrial
5.0	Residential - urban
2.0	Residential - rural
0.5	Agricultural
0.1	Parkland - forested/other
0.05	Remote - forested/other

The index multipliers were established subjectively based on judgement to reflect the perceived variations in activity level associated with the specified land use types. (Note that the primary consideration employed in assigning index multiplier values was population density.)

The crossing factor F_{XING} (line attribute **Crossing** in Table 3.1) is an index that scales R_{ACT} to reflect the impact of pipeline crossings on construction activity level. The crossing types and index multiplier associated with each type are given by the following:

F_{XING}	<u>Crossing / Special Terrain Type</u>
1.0	None (typical cross country)
10.0	Road / Rail
10.0	River / Stream
0.1	Bog / Muskeg / Marsh / Swamp
0.1	Lake
1.0	Aerial

The index multipliers were established subjectively based on judgement to reflect the perceived variations in activity level associated with specific crossing and terrain types.

The probability that the depth of cover is insufficient to prevent contact where construction activity crosses the pipeline as defined by the basic event P_{DPT} is given by

$$P_{DPT} = \left(\frac{0.45}{d} \right)^2 \quad [4.10]$$

Probability Estimation

where, d , is the depth of pipeline burial in metres (line attribute **Cover** in Table 3.1). The form of Equation [4.10] was adapted from a model proposed by Kiefner (1990) and the numerator value was chosen such that the calculated rate of reduction in impact frequency with increased burial depth is consistent with the trend exhibited by historical data reported by the European Gas Pipeline Incident Group (EGIG 1993), assuming that hit frequencies are proportional to the reported failure frequencies.

The probability that the line markings (*i.e.*, general right-of-way condition and/or signage) are not adequate to make the contractor aware of the presence of a pipeline, as defined by the basic event P_{MRK} , is given by

P_{MRK}	<u>Right-of-way Condition / Signage</u>
0.1	Excellent
0.2	Above average
0.3	Average
0.6	Below average
0.9	Poor

The probability estimates associated with each right-of-way condition/signage state (line attribute **ROWcond** in Table 3.1) were established subjectively based on judgement to reflect the perceived variations in effectiveness associated with the specified marking levels.

The probability that the dig notification and response system will not be adequate to make the contractor aware of the presence of a pipeline, as defined by the basic event P_{CALL} , is given by

P_{CALL}	<u>Notification / Response System</u>
0.25	One-call system (high awareness level)
0.5	One-call system (average awareness level)
0.75	One-call system (low awareness level)
1.0	None

The probability estimates associated with each one-call system state (line attribute **Notify** in Table 3.1) were established subjectively based on judgement to reflect the perceived variations in effectiveness associated with the specified levels of dig notification and response.

The probability that the contractor will ignore the line markings or simply fail to miss the pipeline during excavation work, as defined by the basic event P_{ACC} , is assumed to be a random

Probability Estimation

parameter that is not correlated to specific line attributes. It will be characterized by its mean value which is subjectively estimated to be approximately 10% (*i.e.*, $P_{ACC} = 0.1$).

The probability that the interval between right-of-way patrols will be sufficient for construction activity to start and lead to damage between patrols, as defined by the basic event P_{INT} is estimated based on the following assumptions: that the average elapsed time from the start of construction mobilization (visible to patrol personnel) and activity causing failure is 24 hours, and that construction activity is possible 5 days per week. Given these assumptions the non-detect probabilities as a function of patrol frequency (line attribute **ROWpatrol** in Table 3.1) are as follows:

P_{INT}	<u>Patrol Frequency</u>
$(30-1)/30 \cong 1.0$	Monthly (or less frequently)
$(10-1)/10 = 0.9$	Bi-weekly
$(5-1)/5 = 0.8$	Weekly
$(5-2)/5 = 0.6$	Twice per week
$(5-3)/5 = 0.4$	Three or more times week

Finally, the probability that right-of-way patrol personnel will fail to detect activity having the potential to cause line damage during a patrol, as defined by the basic event P_{DET} , is assumed to be a random parameter that is not correlated to specific line attributes. It will be characterized by its mean value which is subjectively estimated to be approximately 5% (*i.e.*, $P_{DET} = 0.05$).

4.2.4.3.3 Probability of Failure Given Interference

Given a mechanical interference event, the probability of failure, P_{FIH} , is equal to the probability that the load, L , will exceed the pipe wall resistance, R , at the location of impact. This can be written as:

$$P_{FIH} = P(L > R) = P(R - L < 0) \quad [4.11]$$

If, as a first order approximation, the uncertainty associated with both the applied load and the pipe resistance are characterized by assuming that both parameters are normally distributed and therefore fully described by a mean value, μ , and a standard deviation, σ , then a solution to Equation [4.11] is given by

$$P_{FIH} = P(R - L < 0) = \Phi \left(\frac{\mu_L - \mu_R}{\sqrt{\sigma_L^2 + \sigma_R^2}} \right) \quad [4.12]$$

Probability Estimation

where: μ_L = the mean value of the applied load;
 σ_L = the standard deviation of the applied load;
 μ_R = the mean value of the pipe resistance;
 σ_R = the standard deviation of the pipe resistance; and

Φ is the standard normal distribution function.

The magnitude of the applied load is a function of the weight of the construction/excavation equipment impacting the pipeline. Based on an estimate of the weight distribution of excavation equipment operating in North America obtained by C-FER from industry, and assuming that the impact force in kN is equal to 5.63 times the excavator weight in tonnes (Spiekhout 1995), the applied load can be characterized by the following

$$\mu_L = 164 \text{ kN}, \quad [4.13a]$$

$$\sigma_L = 73.8 \text{ (cov} = 45\%) \quad [4.13b]$$

A pipeline impact resistance model developed from full-scale tests on line pipe by Spiekhout (1995) is given by

$$R = \lambda(4.8St^2) + \beta \quad [4.14]$$

where: S = pipe body yield strength (line attribute **PipeYield** in Table 3.1);
 t = pipe wall thickness (line attribute **PipeWall** in Table 3.1);

and λ and β are random variables that can be estimated from regression analysis of test results and model predictions.

Based on this model, and representative assumptions about the variability in pipe yield strength and wall thickness, it can be shown that the pipe resistance is characterized by

$$\mu_R = \mu_\lambda 4.8\mu_S(\mu_t^2) + \mu_\beta \quad [4.15a]$$

$$\sigma_R = \left[(4.8\mu_S\mu_t^2)^2 \sigma_\lambda^2 + (\mu_\lambda 4.8\mu_t^2)^2 \sigma_S^2 + (2\mu_\lambda 4.8\mu_S)^2 \sigma_t^2 + \sigma_\beta^2 \right]^{1/2} \quad [4.15b]$$

where: μ_S = mean value of pipe yield strength = 1.1 S ;
 σ_S = standard deviation of pipe yield strength = 0.07 S ;
 μ_t = mean value of pipe wall thickness = t ;
 σ_t = standard deviation of pipe wall thickness = 0.01 t ;
 μ_λ = mean value of λ = 0.73;
 σ_λ = standard deviation of λ = 0.0;
 μ_β = mean value of β = 170 (kN); and
 σ_β = standard deviation of β = 34 (kN).

Probability Estimation

The probability of line failure given impact can therefore be estimated from Equation [4.12] using Equation [4.13] for the load parameters and Equation [4.15] for the resistance parameters.

4.2.4.3.4 Model Scale Factor

The model scale factor K_{MD} serves to adjust the failure rate modification factor to a value of unity for the *mechanical damage reference segment* defined as the line segment associated with the reference value of all line attributes that influence the mechanical damage failure rate estimate. The intention is that the baseline failure rate for mechanical damage should apply directly to the reference segment (hence the need for a corresponding attribute modification factor of 1). The expression for K_{MD} is obtained by first rearranging Equation 4.7 and setting $AF = 1.0$ to give

$$K_{MD} = \frac{1}{P_{HIT} P_{FH}} \quad [4.16]$$

The value of the mechanical damage model scale factor is calculated using Equations [4.8], [4.12], and [4.16] by substituting the values of all parameters that are associated with the reference segment. The reference segment parameter values should be developed in conjunction with the baseline failure rate estimate (see Section 4.2.2) on a pipeline system, operating company or industry basis, depending on the intended application of the model.

Based on a review of incident data summaries in the public domain the following reference values are suggested as default values for the mechanical damage reference segment:

- land use type, **AdjLand** = assume a blended value, $F_{LU} = 1.0$;
- crossing / special terrain, **Crossing** = None (typical), $F_{XING} = 1.0$;
- depth of cover, **Cover** = 0.9 m;
- probability of inadequate line marking, **ROWcond** = Average, $P_{MRK} = 1.0$;
- probability of inadequate one-call, **Notify** = Average system, $P_{CALL} = 0.5$;
- probability of accidental impact with located line = constant, $P_{ACC} = 0.1$;
- probability that patrol interval too long, **ROWpatrol** = Bi-weekly, $P_{INT} = 0.9$;
- probability that patrol personnel miss indication = constant, $P_{DET} = 0.05$;
- pipe wall thickness, **PipeWall** = 5.82 mm; and
- pipe body yield strength, **PipeYield** = 241 MPa (Grade B).

The corresponding model scale factor is $K_{MD} = 6.17 \times 10^1$.

4.2.4.4 Ground Movement

Pipeline failure can occur as a result of ground movement caused by, for example: subsidence, frost heave, thaw settlement, slope movement, and seismic activity. The potential for line failure

Probability Estimation

due to ground movement depends on both the likelihood and extent of movement and the subsequent likelihood of pipe failure given ground movement. Failures due to ground movement events are highly location and pipeline specific and therefore, probability estimation based on historical incident rates adjusted by selected line attributes is not considered appropriate. Alternatively, an approach based entirely on location specific information is employed. Specifically, pipeline failure associated with ground movement will be addressed by directly specifying estimates of both the probability of a ground movement event, and the probability of line failure given event occurrence. These estimates will be inferred directly from the corresponding line attributes.

The failure rate modification factor developed to reflect this approach is

$$AF = R_{MV} P_{FIM} F_{JNT} \quad [4.17]$$

where: R_{MV} = annual rate of significant ground movement events;
 P_{FIM} = probability of pipe failure given movement event; and
 F_{JNT} = pipe joint factor.

Note that for the reasons stated above, this parameter will be multiplied by a fixed baseline failure rate estimate of unity, hence the calculated value of AF represents the estimated failure rate due to ground movement.

The rate of occurrence of a significant ground movement event, R_{MV} (line attribute **GndMovPot** in Table 3.1), is given by

R_{MV}	Rate Estimate (events / km year)
0.00001	Negligible (≤ 1 in 100,000)
0.0001	Low (1 in 10,000)
0.001	Moderate (1 in 1000)
0.01	High (1 in 100)
0.1	Extreme (≥ 1 in 10)

The rate estimates associated with each category were established subjectively based on judgement to provide a usable range of values that should be sufficient to characterize most situations of interest. Note that for line sections containing a single significant ground movement site, the rate estimate would be the annual event probability divided by the section length.

The probability of pipeline failure given ground movement, P_{FIM} (line attribute **GndFailPot** in Table 3.1), is given by

Probability Estimation

P_{EM}	<u>Failure Probability (per event)</u>
0.01	Low (≤ 1 in 100)
0.1	Moderate (1 in 10)
1.0	High (1 in 1)

Again, the probability estimates associated with each category were established subjectively based on judgement to provide a usable range of values that should be sufficient to characterize situations of interest.

The pipe joint factor F_{JNT} (line attribute **JointType** in Table 3.1) is an index that modifies the estimate of the probability of failure given movement to reflect the impact of girth weld quality. The index multiplier associated with each joint type is given by the following:

F_{JNT}	<u>Joint Type</u>
0.5	High quality weld
1.0	Average quality weld
2.0	Poor quality weld
5.0	Mechanical joint

The index multiplier associated with each joint type was established subjectively based on judgement to reflect the perceived effect on failure probability of variations in the strength and ductility of different joint types.

4.2.4.5 Environmentally Induced Crack-Like Defects (stress corrosion cracking)

At the current stage of program development, pipeline failure associated with environmentally induced crack-like defects will be restricted to address stress corrosion cracking (SCC) only. SCC tends to occur in highly stressed regions of pipe that are also experiencing external metal loss corrosion. The factors that are thought to affect the susceptibility of a line to SCC include all of the factors that influence the lines susceptibility to external metal loss corrosion plus: a soil environment conducive to SCC, an operating pressure that generates a hoop stress in excess of the so-called threshold stress for SCC, and the presence of a cyclic component to the hoop stress.

The failure rate modification factor developed to reflect the impact of these factors on the rate of SCC failure is

Probability Estimation

$$\begin{aligned}
 AF &= \left[K_{EC} \left[\frac{A}{t} (T+17.8)^{2.28} \right] F_{SC} F_{CP} F_{CT} F_{CC} \right] F_{SCC} F_{TH} F_{SR} F_{CPF} \\
 &= \left[AF_{for \text{ external metal loss corrosion}} \right] F_{SCC} F_{TH} F_{SR} F_{CPF} \quad [4.18]
 \end{aligned}$$

where: F_{SCC} = SCC potential factor;
 F_{TH} = threshold stress factor;
 F_{SR} = stress range factor; and
 F_{CPF} = supplemental cathodic protection factor.

The premise implicit in Equation [4.18] is that the SCC failure rate will be proportional to the external metal loss corrosion failure rate on the basis that an environment conducive to external metal loss corrosion must exist before SCC can develop. This suggests further that the baseline failure rate that is to be multiplied by the attribute factor defined above is that corresponding to external metal loss corrosion. Given these assumptions, the SCC specific attribute factors listed above therefore serve to define an SCC failure rate as some fractional multiple of the external metal loss corrosion rate. It is assumed that given the current lack of consensus on the mechanisms of SCC initiation and growth in line pipe, this simplistic and potentially conservative approach to failure rate estimation for the purposes of segment ranking represents a prudent interim strategy.

The SCC potential factor, F_{SCC} , (line attribute **SCCPot** in Table 3.1) is an index that modifies the metal loss corrosion factor to reflect the impact of soil environment (*e.g.*, water chemistry and pH) on the SCC failure rate. The index multiplier associated with each condition state is given by the following:

F_{SCC}	<u>SCC Potential</u>
0.0	no potential
0.1	unlikely potential
0.5	likely potential
1.0	definite potential

The SCC potential condition states and associated indices were selected so that if the soil environment is not conducive to SCC, then the SCC failure rate will be zero; and if the soil is definitely conducive to SCC, then the failure rate estimate will (depending on other factors) be equal to the metal loss corrosion failure rate. Intermediate index multipliers have been introduced to acknowledge a finite SCC failure potential in the absence of the information necessary to characterize the SCC potential of the soil environment.

Probability Estimation

The threshold stress factor, F_{TH} , is an index that modifies the metal loss corrosion factor to reflect the impact of hoop stress level on the SCC failure rate. The hoop stress level is defined in terms of a stress ratio given by

$$StressRatio = \frac{PD}{2tS} \quad [4.19]$$

where: P = line operating pressure (line attribute **Press** in Table 3.1);
 D = pipe diameter (line attribute **PipeDiameter** in Table 3.1);
 t = pipe wall thickness (line attribute **PipeWall** in Table 3.1); and
 S = pipe body yield stress (line attribute **PipeYield** in Table 3.1).

The index multiplier associated with each condition state is given by the following:

F_{TH}	<u>StressRatio</u>
0.0	< 0.5
0.5	0.5 to 0.6
1.0	> 0.6

The threshold stress condition states and associated indices were selected to acknowledge that the generally recognized threshold for the initiation of SCC is a hoop stress level of between 50 and 60 % of the pipe body yield strength (Beavers and Thompson 1995). For hoop stress levels below 50 % the threshold index multiplier is 0.0 implying that the SCC failure potential is essentially zero. The uncertainty associated with the threshold stress level is reflected by an index multiplier of 0.5 for stress levels in the transition range.

The stress range factor F_{SR} (from line attribute **PressRange** in Table 3.1) is an index that modifies the metal loss corrosion factor to reflect the impact of cyclic hoop stresses on the SCC failure rate. The index multiplier associated with each condition state is given by the following:

F_{SR}	<u>Pressure Range</u>
0.0	0.0
1.0	>0.0

The stress range factor, as defined, simply acknowledges that SCC growth requires a non-zero hoop stress range (Beavers and Thompson 1995).

The supplemental cathodic protection factor, F_{CPF} , is an index that modifies the metal loss corrosion factor to reflect the impact of cathodic protection on the SCC failure rate. The index

Probability Estimation

multiplier associated with each value of the cathodic protection level attribute (line attribute **CPlevel** in Table 3.1) is given by the following:

E_{CPE}	<u>Cathodic Protection Level</u>	<u>Characterization</u>
1.0	above average	adequate voltage, uniform level
1.0	average	adequate average voltage, some variability
1.0	below average	inadequate voltage and/or high variability
0.0	no cathodic protection	_____

The supplemental cathodic protection factor serves to acknowledge that SCC growth does not occur outside a finite voltage potential range that will not occur naturally on a line without cathodic protection (Beavers and Thompson 1995).

4.2.4.6 Mechanically Induced Crack-Like Defects (metal fatigue)

At the current stage of program development, pipeline failure associated with mechanically induced crack-like defects is restricted to the consideration of seam weld fatigue cracks only. Seam weld fatigue tends to occur in susceptible seam welds (*i.e.*, seams with significant starter defects) that are also undergoing significant stress fluctuations due to line pressure variations and/or external loads. The factors that are thought to affect the susceptibility of a pipeline to seam weld fatigue are primarily seam weld type, effective stress range and number of stress cycles. Failures due to seam weld fatigue are considered highly pipeline specific and therefore, probability estimation based on historical incident rates adjusted by selected line attributes is not considered appropriate. Alternatively, an approach based entirely on location specific information is employed.

The failure rate modification factor developed to reflect the impact of significant factors on the rate of seam weld failure is

$$AF = N_{SW} P_{SWF} \quad [4.20]$$

where: P_{SWF} = probability of seam weld fatigue failure
 N_{SW} = effective number of seam welds per unit line length.

Note that for the reasons stated above, this parameter will be multiplied by a fixed baseline failure rate estimate of unity, hence the calculated value of AF represents the estimated failure rate due to seam weld fatigue.

Probability Estimation

The probability of seam weld fatigue failure P_{SWF} is equal to the probability that the number of load cycles, N_L , will exceed the number of cycles associated with failure at the corresponding stress range, N_R . This can be written as:

$$P_{SWF} = P(N_L > N_R) = P(N_R - N_L < 0) \quad [4.21]$$

If the number of load cycles is treated as a deterministic quantity, and the uncertainty associated with the fatigue life of the weld is characterized by a log normal probability distribution (Albrecht 1983), then the solution to Equation [4.21] is given by

$$P_{SWF} = P(N_R - N_L < 0) = \Phi \left(\frac{\log(N_L) - \mu_{\log(N_R)}}{\sigma_{\log(N_R)}} \right) \quad [4.22]$$

where: $\log(N_L)$ = the log of the number of applied load cycles;

$\mu_{\log(N_R)}$ = the mean value of the log of the fatigue life of the weld seam;

$\sigma_{\log(N_R)}$ = the standard deviation of the log of the fatigue life of the weld seam; and

Φ is the standard normal distribution function.

The number of applied load or pressure cycles is a specified pipeline characteristic (see line attribute **PressCycle** in Table 3.1).

The fatigue life of a weldment, N_R , is typically expressed by a relationship of the form

$$\log(N_R) = b - m \log(S_r) \quad [4.23]$$

where b and m are random variables that can be estimated from regression analysis of fatigue test results, and S_r is the stress range perpendicular to the weldment axis which is given by

$$S_r = \frac{P_r D}{2t} \quad [4.24]$$

where: P_r = the operating pressure range (line attribute **PressRange** in Table 3.1);

D = pipe diameter (line attribute **PipeDiameter** in Table 3.1); and

t = pipe wall thickness (line attribute **PipeWall** in Table 3.1).

Note that where the primary component of cyclic stress is not caused by fluctuating line pressure (say for example where external loads at road crossings are significant), an equivalent operating pressure range, P_r^* , can be specified for the **PressRange** attribute (see Table 3.1) that takes the form

$$P_r^* = \frac{2t S_r^*}{D} \quad [4.25]$$

Probability Estimation

where S_r^* is the maximum stress range perpendicular to the weldment axis due to the loading mechanism in question.

Based on this model, and assuming that a typical line pipe seam weld corresponds to an AASHTO weldment category C, it can be shown (see for example Albrecht 1983) that the fatigue life of the weld is characterized by

$$\mu_{\log(N_R)} = \mu_b - \mu_m \log(S_r) \quad [4.26a]$$

where: μ_b = the mean value of $b = 12.68$;
 μ_m = the mean value of $m = 3.097$; and

$$\sigma_{\log(N_R)} = \text{a constant} = 0.158. \quad [4.26b]$$

The probability of fatigue failure for a typical seam weld can therefore be estimated from Equation [4.22] using the load resistance parameters given in Equation [4.26].

To account for the detrimental effect of poor seam weld quality on fatigue strength, it is suggested that the actual stress range S_r be replaced by an effective stress range S_r' given by

$$S_r' = \frac{S_r}{F_{SM}} \quad [4.27]$$

where F_{SM} is a seam weld factor that reflects the reduction in fatigue life caused by the increased size of starter defects associated with problematic welding processes.

The seam weld factor F_{SM} associated with each value of seam weld type (line attribute **SeamType** in Table 3.1) is given by the following:

F_{SM}	<u>Seam Weld Type</u>
1.0	None (seamless)
1.0	High quality weld
0.8	Suspect weld
0.6	Poor quality weld

The seam weld factor range (1.0 to 0.6) is taken directly from the CSA pipeline code clause dealing with the effect of longitudinal joint type on allowable operating pressure (clause 4.3.3.4, CSA Z662-1994). An intermediate or suspect weld category has been introduced to characterize problematic welds (*e.g.*, pre 1970 electric resistance welds), and the corresponding seam weld factor has been set half way between the upper and lower bound values.

Probability Estimation

Finally, to account for the fact that the model developed above considers only a single weldment, a multiplier is required to convert the probability of failure per seam weld into a probability of failure per unit line length (see Equation [4.20]). Assuming that each pipe joint seam weld constitutes a distinct weldment, and assuming further an average joint length of approximately 10 m, this implies that there are on the order of 100 fatigue susceptible weldments per kilometre of pipeline, hence

$$N_{sw} = 100 \quad [4.28]$$

4.2.4.7 Other Causes

The 'other' causes category is included in the prioritization model to reflect the background failure rate associated with causes that are not typically addressed by maintenance programs intended to maintain the integrity of aging pipelines. In the context of this project it is assumed to be independent of specific line attributes and therefore a constant value. This implies that the failure rate modification factor for failure by other causes is given by

$$AF = 1.0 \quad [4.29]$$

Figures and Tables

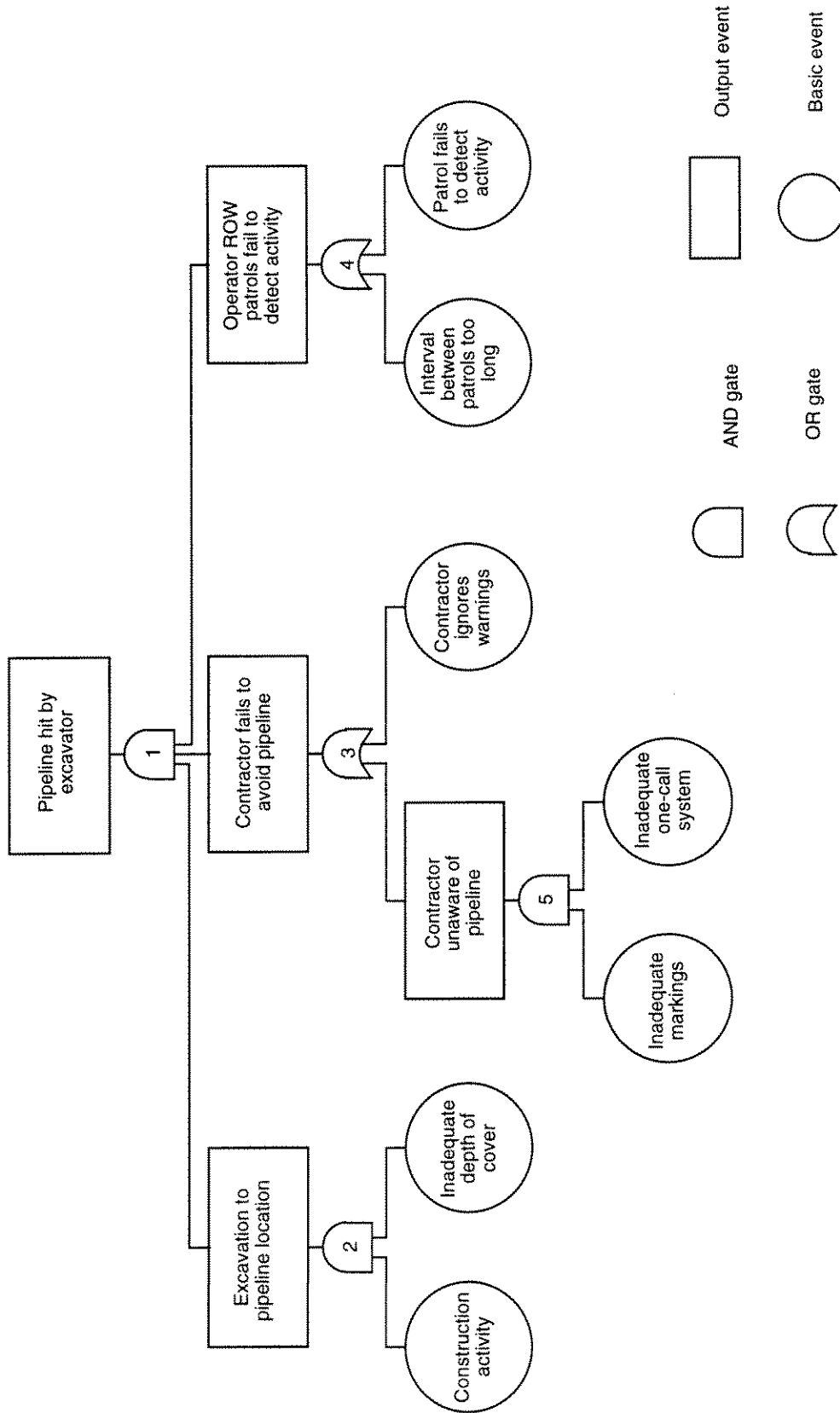


Figure 4.1 Fault tree model for mechanical interference

Failure Cause	Baseline Failure Rate (incidents/km yr)	Mode Factor		
		small leak	large leak	rupture
External Metal Loss Corrosion	3.0×10^{-4}	0.85	0.10	0.05
Internal Metal Loss Corrosion	0.5×10^{-4}	0.85	0.10	0.05
Mechanical Damage	3.0×10^{-4}	0.25	0.50	0.25
Ground Movement	not applicable	0.20	0.40	0.40
Environmental Cracks (SCC)	not applicable	0.60	0.30	0.1
Mechanical Cracks (fatigue)	not applicable	0.6	0.3	0.1
Other Causes	2.0×10^{-4}	0.8	0.1	0.1

Table 4.1 Reference baseline failure rates and relative failure mode factors by cause for buried pipelines

5.0 CONSEQUENCE EVALUATION

5.1 Introduction

An estimate is required of the consequences of line failure for each section within each analysis segment as a function of the mode of line failure. The consequences are calculated for each failure mode using analytical models that have been developed to evaluate product release characteristics and hazard areas and use this information to calculate quantitative measures of the life safety impact, the environmental impact, and the financial impact of line failure. The three distinct consequence components are then combined into a single measure of the loss potential associated with each failure scenario.

Consequence evaluation and combination is carried out for each analysis segment using algorithms that have already been developed and implemented within the framework of an influence diagram that was designed for decision analysis; for further details refer to PIRAMID Technical Reference Manual No. 3.2 (Stephens *et al.* 1996). The influence diagram that forms the basis for the consequence evaluation model used for system prioritization is a modified and somewhat simplified version of the influence diagram described in the report referenced above.

The simplified consequence evaluation influence diagram used for prioritization is shown in Figure 5.1. This influence diagram can be solved to obtain estimates of the three main consequence measures: *Number of Fatalities*, *Equivalent Residual Spill Volume* and *Total Cost*; as well as the combined consequence measure, referred to herein as *Loss*, as a function of *Failure Mode* (*i.e.*, small leak, large leak, and rupture) and *Failure Section* (*i.e.*, attribute consistent sections along the length of the line segment). Note, a detailed discussion of the steps involved in specifying and solving an influence diagram is given in PIRAMID Technical Reference Manual No. 2.1 (Nessim and Hong 1995).

The following section of this report contains a technical description of the node parameters associated with the consequence evaluation influence diagram shown in Figure 5.1 that differ from those in the decision analysis influence diagram developed previously. The reader is directed to PIRAMID Technical Reference Manual No. 3.2 for a technical description of all other 'common' node parameters.

5.2 Consequence Evaluation Influence Diagram Node Parameters

5.2.1 Failure Mode

The *Failure Mode* node is a modified version of the *Pipe Performance* node in the original decision influence diagram (see Technical Reference Manual No. 3.2). The name change reflects

Consequence Evaluation

the fact that the four valid states associated with the original node parameter (*i.e.*, safe, small leak, large leak, and rupture) have been revised down to three with the safe state being eliminated. This reflects the fact that the consequences of the safe state (*i.e.*, no failure) are not relevant to the prioritization model and consequences associated with the no failure state (*i.e.*, the *Maintenance Cost* node) have therefore been eliminated.

5.2.2 Equivalent Volume

The *Equivalent Volume* node in the original decision influence diagram (see Technical Reference Manual No. 3.2) has been modified to reduce the number of line attributes that must be specified to characterize the environmental damage sensitivity of the spill site. The reduced attribute set is shown in Table 5.1 together with the attributes that have been eliminated from the list and defined internally by representative default values. In addition, the node has been revised such that the additional required node parameter inputs (*i.e.*, the reference spill product and the reference spill site damage index) are specified by global model default values.

5.2.3 Interruption Cost

The *Interruption Cost* node in the original decision influence diagram (see Technical Reference Manual No. 3.2) has been modified to calculate unit product transport costs, μ_{trans} , from the following relationship

$$\mu_{trans} = \mu_{trans}^* T_{dist} \quad [5.1]$$

where μ_{trans}^* is the unit transport cost in dollars per unit volume per unit distance, and T_{dist} is the transport distance associated with products passing through the line segment in question. This calculation approach allows for the definition of universal unit transport cost estimates, by product type, that are independent of segment length and therefore globally applicable to the pipeline system as a whole. The unit cost estimates, μ_{trans}^* , can therefore be specified by global model default values. The required segment specific data, T_{dist} , is obtained directly from the data structure generated at the System Definition stage of model specification (see line attribute **TransDist** in Table 3.1).

In addition, the node has been modified such that the remaining segment specific node parameter input data (*i.e.*, the tendered volume vs. line capacity and the billing abatement threshold) are also obtained directly from the data structure generated at the System Definition stage of model specification (see line attributes **CapFraction** and **BAT** in Table 3.1).

Consequence Evaluation

5.2.4 Loss

5.2.4.1 Node Parameter

The *Loss* node is a new node that serves to convert the *number of fatalities* estimate and the *equivalent residual spill volume* estimate into equivalent dollars and to then add these quantities to the *total cost* estimate to produce a combined measure of the total loss associated with line failure in so-called equivalent dollar units. This conversion is carried out based on the so-called 'willingness to pay' concept which involves making an estimate of the amount of money that the pipeline operator, or society as a whole, would be willing to pay to avoid a particular adverse outcome. Using this approach, the cost equivalent of a human fatality can be estimated by determining the amount of money that the operator (or society) would be willing to pay to avoid the loss of a statistical life. Similarly, an estimate can be made of the amount of money that the operator (or society) would be willing to pay to avoid the long-term environmental damage associated with the spill of a reference volume of a specific product at a specific reference location.

The algorithm employed to calculate the node parameter which is total loss estimate, *Loss*, for each mode of failure *k* on each section *j* along each segment *i* is given by:

$$Loss_{ijk} = \bar{c}_{ijk} + \alpha_n \bar{n}_{ijk} + \alpha_v \bar{v}_{ijk} \quad [5.2]$$

- where: \bar{c} = mean value of the *total cost* ;
 \bar{n} = mean value of the *number of fatalities* ;
 \bar{v} = mean value of the *equivalent volume* ;
 α_n = equivalent cost of one human fatality; and
 α_v = equivalent cost of a unit residual spill volume of reference product at the reference spill location.

5.2.4.2 Equivalent Costs

As indicated previously, the equivalent cost of human fatalities and equivalent spill volumes can be estimated using the willingness to pay (WTP) approach. As developed in the economics literature, and summarized by Rusin and Savvides-Gellerson (1987), the WTP approach, when applied to the value of human life, takes into account an individual's desire to improve their probability of survival by estimating what the individual would be willing to pay for a marginal reduction in their probability of death. Specifically, the WTP method measures the value of goods and services that an individual would be willing to forego in order to obtain a reduction in the probability of accidental loss of life. By averaging this measure across all people exposed to a risk, or a potential change in risk, an estimate of the value of a statistical life is obtained.

Consequence Evaluation

In the Rusin and Savvides-Gellerson study cited above, a review of economic studies undertaken by various government agencies and consulting firms led the authors to adopt an estimate of \$2 million dollars as “the value of reducing the risk of death by an amount such that we expect one less death at the reduced risk level”. This monetary value is suggested here as a default estimate of the equivalent cost of one human fatality in the absence of a formal evaluation of this cost by the user of the prioritization method.

Similarly, the WTP approach can be applied to equivalent spill volumes wherein an estimate can be obtained of the value of goods and services that an individual would be willing to forego in order to obtain a reduction (or to prevent an increase) in the probability of long-term environmental damage resulting from a unit volume of reference product spilled at a reference location. Given the implicit variability in the actual and perceived impact of different spill products on different environments, it is difficult to come up with a broadly applicable estimate of the equivalent cost (in $\$/\text{m}^3$) of an equivalent spill volume; this quantity is highly operator and location specific.

To provide a point of reference for environmental damage cost equivalents, consider the following. A hypothetical environmental damage assessment case presented by Desvousges *et al.* (1989) indicates an equivalent cost in the range of $\$20,000/\text{m}^3$ to $\$200,000/\text{m}^3$ for a diesel oil spill (with a residual spill volume of approximately 100 m^3) in an environmentally sensitive recreational area. Note that the low end of the cited cost range considers site restoration costs only, whereas the high end of the range reflects the additional loss-of-use value and the so-called non-use value of the damaged resources to people far removed from the spill site who would be willing to pay to simply know that the environmental resource exists and that it is available for use if desired.

As another example, the state of Washington has developed a spill damage compensation formula for estimating public resource damages for oils spills into state waters (Geselbracht and Logan 1993). This formula assigns a damage cost that falls within a range of $\$260/\text{m}^3$ to $\$13,000/\text{m}^3$ ($\$1/\text{USgal}$ to $\$50/\text{USgal}$) depending on the product damage potential and resource vulnerability.

Based on the cited examples, an equivalent unit cost for equivalent spill volumes, referenced to an environmentally sensitive spill location, could easily be on the order of thousands or tens-of-thousands of dollars. A monetary value of \$10,000 is suggested here as a default estimate of the equivalent cost of a cubic metre of equivalent spill volume (referenced to an environmentally sensitive location) in the absence of a formal evaluation of this cost by the user of the prioritization method.

Figures and Tables

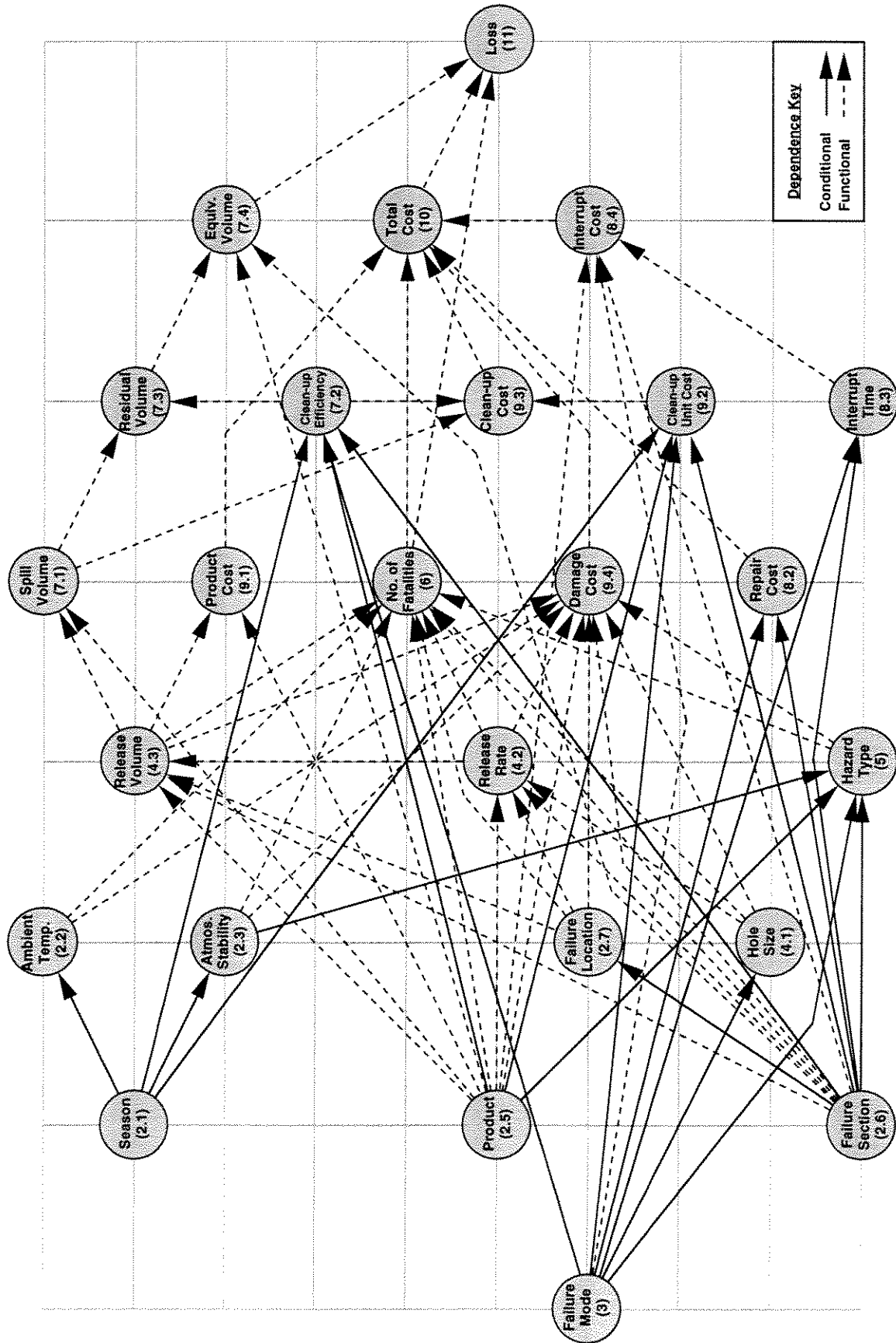


Figure 5.1 Basic node influence diagram for consequence evaluation

Pipeline Segment Attribute	Defined by Program User	No Input Required (specified internally using a representative attribute value)
Adjacent Land Use	X	
Near Field Terrain	X	
<i>Significant Far Field Terrain Character</i>		Same as 'Near Field Terrain'
<i>Natural Surface Containment</i>		None
Distance to Surface Water	X	
<i>Surface Topography</i>		Rolling Terrain (slopes 5 to 50%)
<i>Annual Rainfall</i>		800 mm/yr
<i>Flood Potential</i>		flood return period 20 yrs
<i>Confining Layer Thickness</i>		3 to 10 m
<i>Confining Layer Conductivity</i>		medium (10e-4 to 10e-6 cm/s)
<i>Aquifer Conductivity</i>		medium (10e-2 to 10e-4 cm/s)
Drinking Water within 5km	X	
Other Water within 5km	X	
Land Use within 5km	X	
Sensitive Environment within 10km	X	
Sensitive Groundwater within 10km	X	

Table 5.1 Segment attributes required by Equivalent Volume node to characterize environmental damage sensitivity of spill site

6.0 RISK ESTIMATION AND SEGMENT RANKING

6.1 Introduction

Multiplication of the segment-specific failure probability estimate for a given failure cause by the associated combined loss estimate produces an estimate of operating risk defined as the expected annual loss, $ExpLoss$, associated with a given segment of pipeline for the failure cause in question. Summation of the risk estimates for all failure causes associated with a given segment gives an estimate of the total expected annual loss associated with segment operation. Dividing these segment risk estimates by the corresponding segment length yields normalized risk estimates, $ExpLoss^*$, that allow comparison of calculated risks between segments of different lengths. These cause-specific and combined-cause risk estimates form the basis for a quantitative ranking of all segments identified within a given pipeline system.

6.2 Risk Calculation Model

The expected annual loss $ExpLoss$ associated with each failure cause l for each analysis segment i , is given by:

$$ExpLoss_{il} = \sum_{j=1}^{Ns_i} \sum_{k=1}^{Nm} ExpLoss_{ijkl} \quad (\$/\text{year}) \quad [6.1]$$

where: $ExpLoss_{ijkl} = Pf_{ijkl} Loss_{ijk}$;

Pf_{ijkl} = probability of failure for section j of segment i
associated with failure mode k and failure cause l (failures / year);

$Loss_{ijk}$ = combined loss associated with failure on section j of segment i
resulting from failure mode k (\$ / failure);

Ns_i = number of sections in segment i ; and

Nm = number of failure modes = 3.

The expected annual loss associated with each analysis segment for all failure causes combined is calculated from the following:

$$ExpLoss_i = \sum_{l=1}^{Nc} ExpLoss_{il} \quad (\$/\text{year}) \quad [6.2]$$

Risk Estimation and Segment Ranking

where: N_c = number of failure causes = 7.

The expected annual loss on a per km basis, $ExpLoss^*$, is calculated from the per segment quantities, $ExpLoss$, as follows:

on a cause-by-cause basis

$$ExpLoss_{ii}^* = \frac{ExpLoss_{ii}}{Lseg_i} \quad (\$/\text{km}\cdot\text{year}) \quad [6.3]$$

and for the all causes combined case

$$ExpLoss_i^* = \frac{ExpLoss_i}{Lseg_i} \quad (\$/\text{km}\cdot\text{year}) \quad [6.4]$$

where: $Lseg_i$ = length of Segment i (km).

6.3 Risk Ranking Model

The probability weighted or expected loss estimates, calculated as described in the previous section, form the basis for the ranking of all specified segments. The basic intention is to rank each segment by failure cause to target high risk segments and associated failure causes for subsequent maintenance decision analysis. The option also exists to rank segments on a combined cause basis which will provide a global measure of risk exposure for each segment. The form of the risk ranking output generated by the prioritization model is illustrated in Figure 6.1.

Figures

Segment Risk Ranking

System: Northern Alberta

Date: 8/23/1995

Failure Causes Considered:

External Corrosion	SCC	Mechanical Damage	Other
Internal Corrosion	Seam Weld Fatigue	Ground Movement	
All Causes Combined			

Risk Ranking	Segment Designation	Failure Cause	Expected Cost	
			(\$/km*yr)	(\$/seg*yr)
1	Loop 13	External Corrosion	9,999	199,000 ↑
2	Loop 13	SCC	8,678	180,000
3	Loop 8	Ground Movement	8,000	80,000
4	Loop 12	External Corrosion	6,699	120,000
5	Loop 1	External Corrosion	5,010	225,888 □
6	Loop 2	External Corrosion	5,000	120,000
7	Loop 2	Mechanical Damage	4,400	100,999
8	Loop 3	Mechanical Damage	4,333	43,330
9	Loop 13	Mechanical Damage	3,322	74,900
10	Loop 12	Internal Corrosion	3,009	62,000 ↓

Figure 6.1 Output format for segment risk ranking

7.0 SUMMARY

The system prioritization stage is intended to identify segments within a pipeline system that may present an unacceptable level of operating risk. To this end pipeline characteristics (or attributes) are evaluated to produce a line-specific estimate of the failure rate for each segment within the system as a function of failure cause (*e.g.*, metal loss corrosion; mechanical damage; ground movement; crack-like defects), and an estimate is made of the potential consequences of segment failure in terms of three distinct consequence components (*i.e.*, life safety, environmental damage, and economic impact). Cause-specific failure rates are then combined with a global measure of the loss potential associated with the different consequence components to produce a single measure of operating risk for all failure causes associated with each segment. Segments are then ranked according to the estimated level of risk, the intention being to identify (or target) potentially high risk segments for subsequent detailed decision analysis at the maintenance optimization stage of the pipeline maintenance planning process.

In the context of the prioritization model developed herein, the components of operating risk are estimated as follows:

The probability of line failure is given by

$$Pf_{ijkl} = Rf_{ijkl} Lsec_{ij} \quad (\text{per year}) \quad [4.1]$$

where: Rf_{ijkl} = the failure rate associated with section j of segment i for failure mode k and failure cause l ; and

$Lsec_{ij}$ = the length of section j within segment i (km).

The segment specific failure rate is given by

$$Rf_{ijkl} = Rfb_l MF_{kl} AF_{ijl} \quad (\text{per km}\cdot\text{year}) \quad [4.2]$$

where: Rfb_l = the baseline failure rate for failure mode l (per km \cdot year);

MF_{kl} = the relative probability or mode factor for failure mode k associated with cause l ; and

AF_{ijl} = the failure rate modification factor for section j of segment i associated with failure cause l .

A combined measure of the consequences of line failure is given by

$$Loss_{ijk} = \bar{c}_{ijk} + \alpha_n \bar{n}_{ijk} + \alpha_v \bar{v}_{ijk} \quad (\$ \text{ per incident}) \quad [5.2]$$

Summary

- where: \bar{c} = mean value of the total cost;
 \bar{n} = mean value of the number of fatalities;
 \bar{v} = mean value of the equivalent volume;
 α_n = equivalent cost of a human fatality; and
 α_v = equivalent cost of a unit residual spill volume of reference product at the reference spill location.

The operating risk per segment is given by the probability weighted or expected Loss which on a cause-by-cause basis is given by

$$ExpLoss_{it} = \sum_{j=1}^{Ns_i} \sum_{k=1}^{Nm} ExpLoss_{ijk} \quad (\$/\text{year}) \quad [6.1]$$

where: $ExpLoss_{ijk} = Pf_{ijk} Loss_{ijk}$

- and: Pf_{ijk} = probability of failure for section j of segment i associated with failure mode k and failure cause l (failures / year);
 $Loss_{ijk}$ = combined loss associated with failure on section j of segment i resulting from failure mode k (\$ / failure);
 Ns_i = number of sections in segment I; and
 Nm = number of failure modes = 3.

The normalized operating risk, expressed on a per unit length basis is given by

$$ExpLoss_{it}^* = \frac{ExpLoss_{it}}{Lseg_i} \quad (\$/\text{km}\cdot\text{year}) \quad [6.3]$$

where: $Lseg_i$ = the length of segment i (km)

8.0 REFERENCES

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